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Chemical Education

A CHIMIA Column

Topics for Teaching: Teaching Chemistry at University Level

Units – Student's Friend or Fiend?

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Abstract: The idea behind this column is to point out the difficulties that students or pupils often have when solving problems that require handling units. These include the use of the proper unit for the corresponding physical quantity during the calculation, analysis of the units and providing the result as a numerical value with the correct unit. A wish to join the efforts of all teachers to solve this problem is also expressed.

Keywords: Conversion of units · Dimensional analysis · Science education · Units of measurement

This column probably differs a bit from those that are usually published here, but its content certainly relates to chemical education. I have been in charge of first year chemistry service lectures at ETH for the past three years, which means that although I belong to the Department of Chemistry and Applied Biosciences, I teach chemistry lectures for students at other ETH Departments, *e.g.* students of environmental, agricultural, material or pharmaceutical sciences. With a pinch of irony, I sometimes say that I have those students in my chemistry courses who did not want to study chemistry. However, this discipline is inevitable for their future activities related to studies or research – a fact that strikes them right at the beginning of their sojourn at ETH.

Chemistry teachers from high schools often ask me, what do I require or expect from the students at the beginning of my course. I would be pleased to tell them that I can profit from their excellent work in many ways, but the fact is that the audience is extremely heterogeneous based on every aspect – *e.g.* origin, mother tongue, education, working attitude and most importantly their previous experience with chemistry. 60–70% of my students claim to previously deal with this subject only in a basic course ('Grundlagenfach'). This means that they typically did not pass a school-leaving examination in chemistry and, most importantly, their last school year at a high school was chemistry free. So I have to disappoint my colleagues, but it is difficult to define a suitable starting line and the very first lecture of my course covers the basic aspects of the atomic structure as the starting point. Nevertheless, the work of all high-school teachers is highly appreciated and I am thankful for their efforts to present chemistry in an attractive way. Many of the successful students state that the knowledge acquired already in the high school helped them to pass the chemistry exam at ETH.

But there is something that I would like to put on the wish list. A skill that I expect from those who hold a school-leaving certificate in their hands. An automatism that can be acquired not only during chemistry lessons, but should result from the conceptual work also in other technical disciplines – mostly mathematics or physics. A feature that is also a part of our daily life, although we do not conceive it in a scientific way. But as we (students including) automatically indicate a unit, when we talk about amounts at home or in the shop, it should be a matter of course to consequently use the units in science. For reasons unclear to me and others dealing with teaching chemistry, the reality is different.

The audience of my courses is large (typically 400–500 students) and so I have "the great pleasure" to deal with a large body of exams every examination session. Scoring exams gives me, however, a unique opportunity to witness the ability of students to sometimes provide answers in strong discordance with what has been taught in the course. The following section contains real examples dealing with unit problems. You may think that these are just a couple of extreme cases, a statistical sample, which appears in every exam set. The fact is that the author's collection of such 'mishaps' is much larger, although no quantification has been done so far. It has to be emphasized that the examples shown in the following section stem from the exam sheets and were transferred in their authentic form without any corrections or improvement of the visual presentation. The results are typically wrong, but it is not the role of this article to deal with the master solution. I would like to point at the usefulness of using the correct units in order to avoid making mistakes, losing points, and failing the exam.

The first example depicts a rather extreme case, where the units were entirely ignored. Mathematical operations with several thermodynamic equations are particularly sensitive to the proper use of correct units and the ideal gas law is one of them. In this given problem the volume of acetylene formed in the reaction of calcium carbide with water under standard conditions at 25 °C had to be calculated. The issues related to a variety of units, which can be used with temperature and pressure, can be easily avoided if all units are involved and the dimensional analysis properly carried out (Fig. 1). Thus, when the calculation includes the gas constant, the temperature has to be expressed in kelvin and the pressure in pascal.

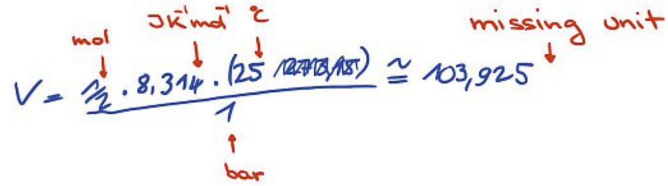

Fig. 1. An example of calculating the volume of a gas without any units. The blue writing in this and all other examples in this article are real answers taken from the first-year chemistry exam, anonymously, and from different students. There is no intention of highlighting any particular student. The red writing is added by the author.

In the next example, which is related to the same problem of the acetylene volume, an alternative strategy involving standard molar volume was applied (Fig. 2). The solution is formulated in a clean and legible way, units are included in the calculation and the result is given in litres, which is a unit relevant for volume. The student thus obviously had no doubts about the correctness of the solution. Had he or she only cared to check the units properly, it would be immediately apparent that mol^2L^{-1} does not come with the volume. Subsequently, the error in the formula should be recognized as the amount of substance has to be multiplied with the standard molar volume.

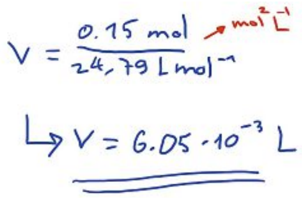

Fig. 2. An example of how dimensional analysis could reveal a mistake in a formula.

Another case relates to a problem of calculating the standard molar entropy of vaporisation of water, whereas a variety of thermodynamic values related to water was given. Albeit the necessary job has been done and all units are included, the dimensional analysis contains a fundamental mistake of cancelling the prefix kilo with the unit kelvin (Fig. 3). The great benefit of the proper usage of the units is the advantage to control whether the result is correct. In this particular case it should be recognized that the resulting unit $Jmol^{-1}$ does not correspond to standard molar entropy ($[S] = JK^{-1}mol^{-1}$) suggesting that the calculation was erroneous.

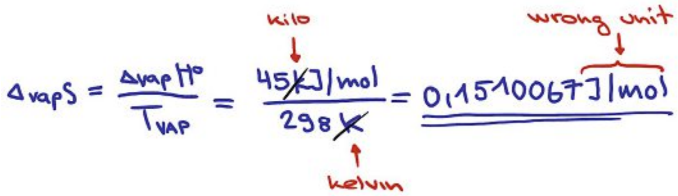

Fig. 3. An incorrect dimensional analysis leads to a wrong unit.

A careful eye of the reader probably noticed another aspect of the above-mentioned solution, which would actually merit a discussion in a separate article. The proper use of significant figures remains challenging, an issue that is probably related to the fact that the students are not familiar with their meaning.

It might be related to lack of time during the examination, but a common mistake involves an incomplete use of units as depicted in the Fig. 4. The problem dealt with the calculation of the pressure of a gas in a container with certain volume, whereas the amount of substance and the temperature were known. The ideal gas law was correctly applied but the unit of concentration is missing as shown in Fig. 4. The result is thus numerically correct, but the unit is wrong. This is another example, when lecturer just remains astounded – how come that students do not recognize that pressure, a quantity present also in daily life, should not be expressed in Joules? The presented graphic also indicates another problem – the dimensional analysis is often not being done at all, although units were (at least partially) included. In this case, $Jmol^{-1}$ would result from such operation, giving the student another chance to reconsider his/her approach.

Finally, I would like to mention a case that depicts that a proper understanding of units can prevent the performing of an impossible mathematical operation. The students were asked to compare the reaction rates of the decomposition of nitrogen dioxide at 50 and 0 °C. The Arrhenius activation energy for that process was given. Although the Arrhenius equation was properly applied to derive the relationship between two rate constants at two different temperatures, the calculation was not carried out properly as the difference between degree Celsius and kelvin was not considered (Fig. 5). It remains elusive, how the value, which is of course wrong, was actually obtained.

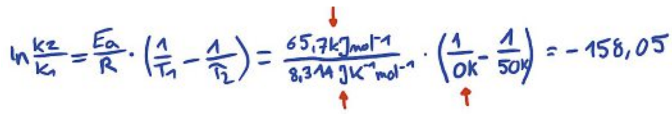

Fig. 5. Ignoring the differences between the units can lead to unsolvable mathematical operations.

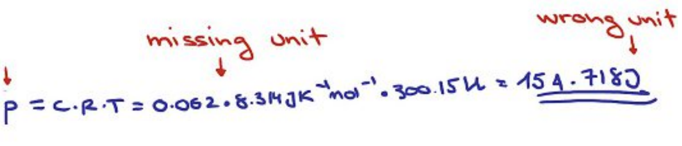

Fig. 4. An inconsistent use of units during the calculation results in an incorrect unit accompanying the numerical result.

There are many more 'pearls' of similar kind in my collection, but I think that many of the readers involved in teaching science have, to a certain extent, a comparable experience. I assume that some of you chuckled at these examples, but the point of this contribution was certainly not to laugh at students' performance. I never do. I just would like to enhance the awareness of this problem. These young people will soon face situations in which unit-related errors may lead to more serious problems than losing points in the exam.

I do not blame anyone because I would have to start with myself. I have never met a teacher who would not consider the units important. So what can be done? I usually include unit-related mistakes in my lecture to directly address the aftermaths of such mistakes. Typically, in a lecture for the pharmacy students we calculate the concentration of some biologically active compound in a mixture and discuss the possible consequences of including g L^{-1} instead of mg L^{-1}. As the audience activity in the large lecture halls is quite often rather lukewarm due to shyness, I tend to mention in an anecdotic manner that I fear a possible scenario of entering a pharmacy in the future and recognizing one of my students at the other side of the counter. Such comments typically bring some smile to their faces and refresh the atmosphere a bit, but more importantly, one could say that the take-home message is clear. Unfortunately, the examples in this column taken from the exams demonstrate that the effect does not last in every student's mind equally long. Or alternatively, the message does not reach every student. Despite the fact that I am aware of the problem with the units and thus the emphasis on their importance in my lectures and exercise sessions increases every year, I can only address those who read the lecture materials and emails, come to the lecture halls or at least watch the recordings.

That is why I wish to join the efforts of all lecturers and teachers at every level, especially of those that have a closer interaction with the pupils (the first tasks dealing with units are introduced already in the primary school). Together, we should design a strategy that would help the young generation of future specialists to acquire this skill, which is crucial and highly relevant in all areas of their careers and lives. There are various platforms with focus on chemistry education,[1-3] which are suitable to cover such initiatives, and it would be great to hear about others.

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[1] Division of Chemical Education of the Swiss Chemical Society: https://www.scg.ch/component/page/chemical-education
[2] Verein Schweizerischer Naturwissenschafts-lehrerinnen und -lehrer (VSN): http://www.vsn.ch/
[3] HSGYM-Project: https://www.hsgym.ch/